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In January 2006, the Stardust spacecraft will deliver its Sample Return Capsule (SRC) to the recovery site at the Utah Test and Training Range (UTTR) in N. Utah. Stardust will return dust samples from comet Wild 2 collected in January 2004, as well as interstellar dust collected at earlier epochs in heliocentric orbit. During Earth return, the trajectory will be perturbed by small firings of the spacecraft reaction control thrusters. Calibration of these firings is essential to ensure meeting Earth entry requirements. This paper will describe such calibrations performed between superior conjunctions in June-July 2003 when Stardust was about 1 AU from the Sun. Results of their subsequent analysis indicate that although more work remains to be done, modifications of the maneuver execution sequences and attitude transition strategies greatly increase the chances of mission success.

MISSION BACKGROUND

The Stardust spacecraft was launched on February 7th, 1999 from the Kennedy Space Center on a Boeing Delta-2 launch vehicle. High points of the mission trajectory include an Earth flyby in December 2000, two episodes of interstellar dust sample collection in Feb.-May 2000 and Aug..-Dec. 2002, and the flyby of comet Wild-2 in January 2004 (see Figure 1).

The science goals of the mission include:

- Acquire interstellar dust samples.
- Acquire 500 comet coma dust samples during flyby of comet Wild-2 on Jan. 2nd, 2004.
- Obtaining images of the nucleus of comet Wild-2 during approach, closest approach and departure.
- Measure quantity and quality of particles impacted during flyby using the Dust Flux Monitor Instrument (DFMI)
- Perform spectroscopic analysis of chemical composition of particles observed using the Cometary and Interstellar Dust Analyzer (CIDA).

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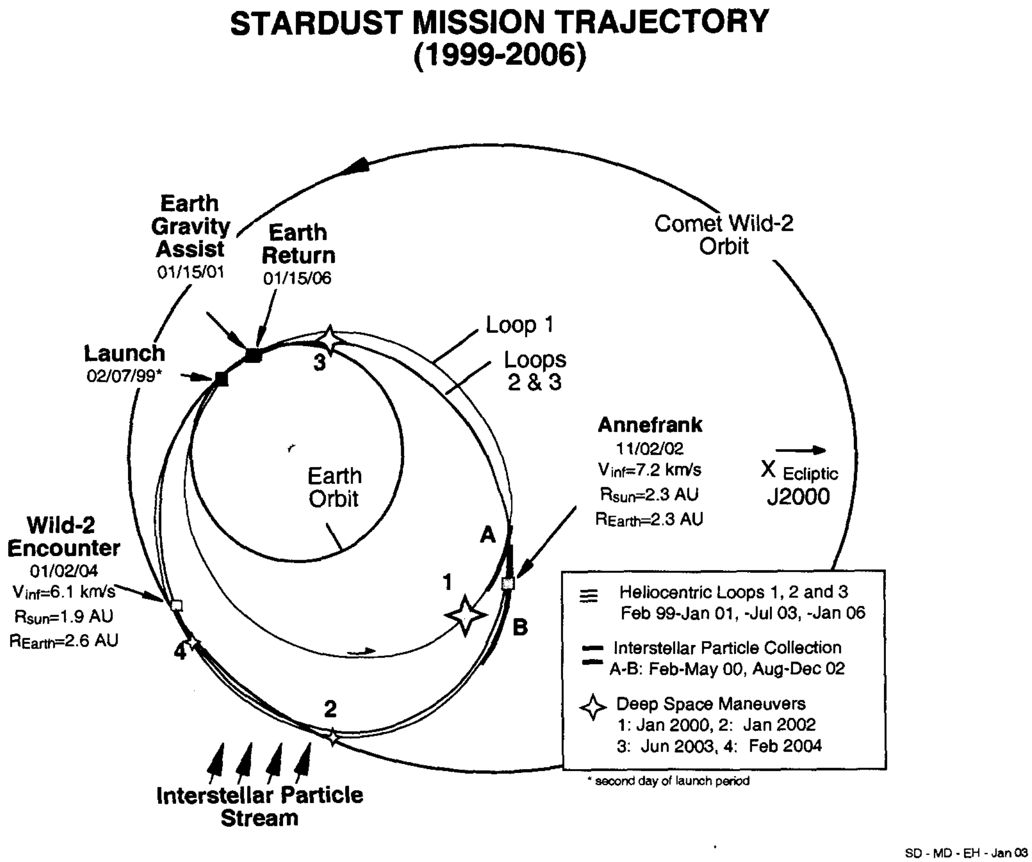

Figure 1. Stardust Mission Trajectory

At this time all major milestones of the mission have been achieved, with one major exception: the return of all collected dust and particle samples to Earth. Of prime importance is the abundance of comet coma particles that are presumed to have been collected based on the number of particle hits seen in the DFMI. This return is scheduled for January 15th, 2006.

Pre-launch, the timeline for the Earth Return Trajectory Correction Maneuver (TCM) schedule was laid out as follows:

- November 16th, 2005: TCM-17 (Return -60 days)
- January 2nd, 2006: TCM-18 (Return -13 days)
- January 14th, 2006: TCM-19 (Return -1 day)
- January 15th, 2006: Separation (Return - 4 hours)

Figure 2 shows an Earth-centered view of the Ecliptic plane in a rotating frame. In this figure, the location of the spacecraft with respect to Earth is shown for each of these events.

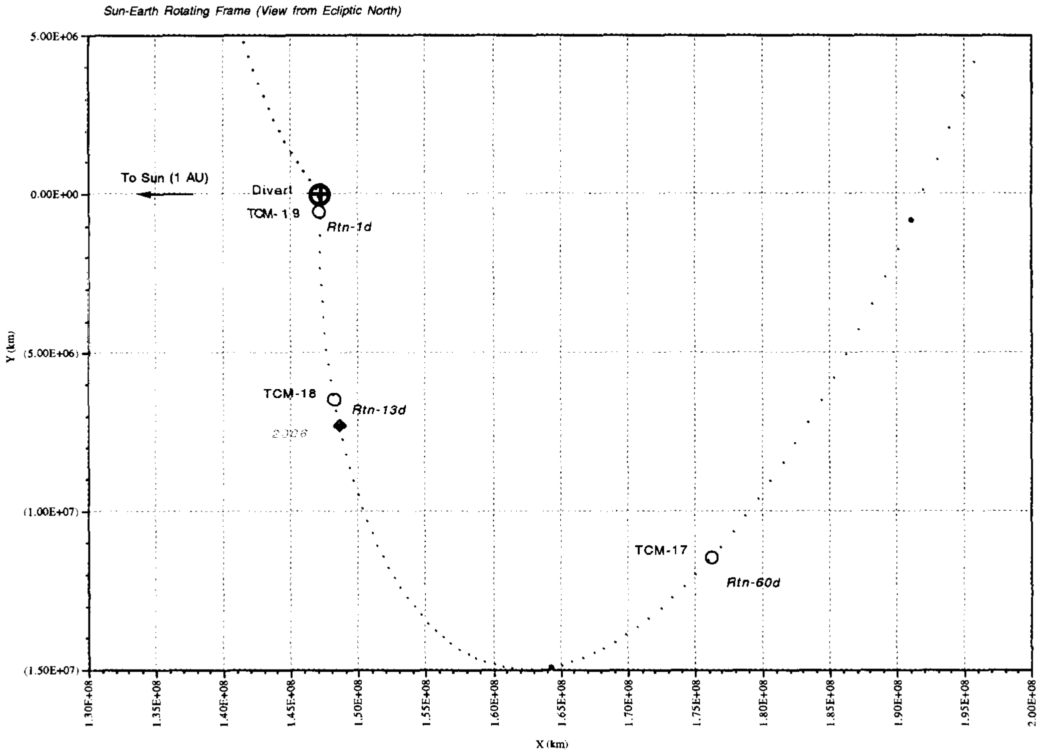

Figure 2. Spacecraft trajectory at Earth Return (Sun-Earth Rotating Frame - view from ecliptic north).

Post-launch, it was noted that uncertainties in spacecraft thruster-related activities were larger than pre-launch studies had predicted. Since these activities might adversely impact the success of returning the capsule to Earth, the Navigation team developed a new plan that minimized the effects of these uncertainties. To this end the overall uncertainties of spacecraft non-grav characteristics needed to be carefully considered in order to develop and execute an extensive non-grav observation plan. Once observed, the non-grav activities were then calibrated and folded into Earth Return studies, which could be used to assess the new chances of mission success.

This paper will discuss the non-grav behaviors of the spacecraft, the plan to observe them, and the calibrations arrived at based on the observed data. The use of these calibrated data in Earth Return studies is described in a concurrent paper [1].

SPACECRAFT CHARACTERISTICS

The Stardust spacecraft, shown in Figure 3, utilizes a three-axis attitude control system (ACS), which includes star trackers, backup analog sun sensors and an inertial measurement unit (IMU) with gyros and accelerometers allowing for some closed-loop control of propulsive events or TCMs. Thrusters are located on the opposite side of the space vehicle from the deployed position of the sample collector to minimize contamination of samples. This includes two strings (prime and backup) of four main thrusters (1 lbf each) used for TCMs and four reaction control subsystem (RCS) thrusters (0.2 lbf each) supporting attitude control and turns ("slews") before and after a main thruster burn. Since such thrusters (positioned and oriented as shown in Figure

4) do not produce balanced torques, all attitude control activities contribute a translational delta-velocity (Δv) that lies nominally in the direction of the spacecraft +z axis. These small forces must be accounted for in orbit determination (OD) processes and in the design of TCMs.

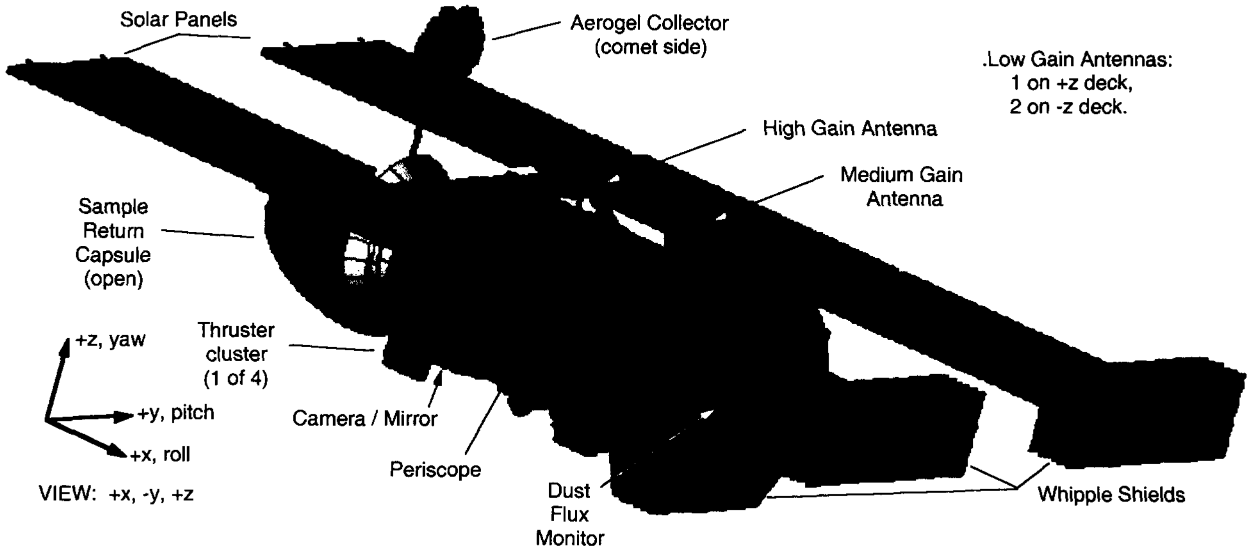

Figure 3. Stardust Spacecraft Overview

Stardust characteristics: TCMs and Slews

TCMs performed by Stardust thus far have proven difficult to predict accurately. In particular, fixed errors, originally estimated before launch to be only 2 mm/sec, 1-sigma [2], have grown as large as 5 to 7.5 cm/sec, after reconstruction of TCMs. While this level of error is acceptable for much of the mission, including the approach to comet Wild 2, such error is unacceptable in terms of achieving the ±0.08 deg, 3-sigma, flight path angle error required for successful delivery of the Sample Return Capsule (SRC) at Earth entry in January 2006. The larger execution error arises from "bang-bang" controlled slews and settling associated with clamping and other components of the TCM sequence itself, effects which are difficult to predict. For slews, the spacecraft changes orientation by accelerating to a maximum turn rate near the initial attitude with corresponding deceleration and settling near the target attitude. This is accomplished exclusively via RCS thrusting. These slews are used to turn to the TCM attitude, then back to Earth pointing for communications purposes. Settling Δv in particular has been difficult to model accurately, perhaps because of sloshing of fuel inside tanks and flexing of various structural components.

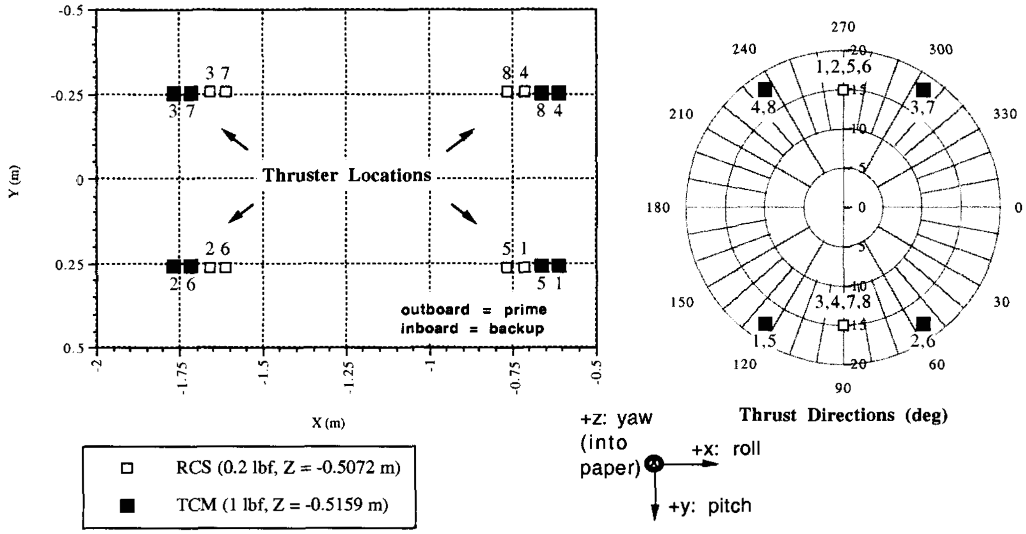

Figure 4. Thruster Configuration for the Stardust spacecraft

Stardust Characteristics: Deadband Attitude Control

For periods between maneuvers, limit cycling or deadband control has been employed to maintain attitude within deadbands of various sizes. For the period prior to Earth return, use of ±0.25 deg deadbands (requiring the IMU to be activated) is planned to provide accurate attitude control for release of the Sample Return Capsule (SRC). During the bulk of the mission, larger deadbands (2, 6 and 15°) have been preferred to limit use of the IMU within a limited operational lifetime. However, larger deadbands can often be one-sided due to solar torque effects. The RCS response to this one-sided deadbanding, and to clamping from larger deadbands down to the tighter 0.25 deg, is difficult to predict accurately, in part because of the randomness of the starting point within the deadband box. Maintaining a tighter deadband over a long period has the benefit of maximizing the predictability of acceleration achieved over time from RCS thruster firings, as long as the IMU lifetime is not exceeded prior to Earth entry.

Stardust Characteristics: Deadband "Walks"

As an alternative to "bang-bang" slews, it is possible to turn the spacecraft by slowly adjusting the deadband box to move towards a target attitude. Such deadband walks involve a maximum turn rate of about 1-1.5 deg/min and are therefore practical only for attitudes close enough to the Sun such that a healthy power state can be assured over substantial time periods. Although deadband walks have not been used to support TCMs thus far, their application for TCMs near Earth entry is made possible by biasing those maneuvers (i.e., introducing a deterministic velocity change into the reference trajectory) in such a way that the burn attitude will be close enough to the Sun (e.g., 45 or 60 deg) that power margin does not become an issue in the time required to execute the deadband walks. With deadband walks, fixed errors comparable to the 2 mm/sec, 1-sigma, pre-launch estimates for TCMs are considered an achievable goal.

NEW PLAN FOR EARTH RETURN

The large uncertainties associated with small forces events led to the following redesign of the maneuver return strategy, in order to return the SRC safely to Earth. A new baseline plan for Earth return, involving biased TCMs and including the introduction of a new TCM-20 at a fixed attitude compatible with conditions for SRC release, is outlined in Table 1. Further refinements to this plan are possible, once the errors are better understood, to achieve Earth entry requirements.

Event	Epoch (ET)	Time from Earth Entry	Δv Bias (m/s)	Notes	Previous plan
TCM-18	02-Jan-2006 18:01:04	-13 days	1	Sunward bias direction	Unbiased (stat. only)
TCM-19	14-Jan-2006 09:58:11	-1 day	1	+z direction at SRC release (~26° off Sun), Sun in xz plane	Unbiased (stat. only)
TCM-20	14-Jan-2006 21:58:11	-12 hours	0.5	Fixed aimpoint, rolled 18° from TCM-19 bias attitude	N/A
SRC Release	15-Jan-2006 05:58:11	-4 Hours	0.3408	Along Earth-based SRC velocity at 100 km altitude (effect on SRC only)	---
Entry	15-Jan-2006 09:58:11	---	n/a	FPA = -8.2°, Alt. = 125 km, RA = 139.924°, Dec = 41.823°	---

Table 1. New Baseline Plan Recommended for Earth Return

TEST OBJECTIVES AND PLANNING

To meet the entry requirements in the context of the new Earth return plan, it was considered essential to acquire appropriate data that would allow the characterization of TCM performance and associated attitude control behavior of the spacecraft. Calibration data would include on-board small forces data, calculated in real time on board the spacecraft for later transmission to the ground, and real-time Doppler and ranging data gathered on the ground whenever the test allowed the spacecraft to be pointed at or near the Earth. The test plan was targeted for the period from June 23 through July 3, 2003. This period coincided with the interval between the third Deep Space Maneuver (DSM-3) on June 17-18 and TCM-9 on July 16, during which the spacecraft would reside at about 1 AU solar distance. Solar radiation pressure and thermal effects were expected to match conditions similar to those expected during Earth Return, affording the best opportunity to characterize the attitude control behavior prior to Earth approach and entry.

There were three broad objectives:

1) Demonstrate series of 0.25 deg deadband walks (DBW) within execution error of 1 cm/sec, 1-sigma, or better for set of walks (pitch-roll-roll-pitch or roll-pitch-pitch-roll, per definitions of roll and pitch about x and y axes, respectively, as indicated in Figure 3) associated with a full TCM design. It is highly desirable (and possibly necessary for mission success) that all attitude changes near Earth return be performed using deadband walks. Turns of 5, 15 and 40 deg were utilized, the former two performed relative to the medium gain antenna (MGA) at 7 deg from +z towards +x, in order to be fully observable from the ground throughout the test. The 40 deg turns were limited to pitches only to avoid potential power loss from shadowing of

the solar panels; since not fully observable from the ground, like some of the limit cycle tests, these were performed between passes and assessed on the basis of OD-reconstructed small forces data.

2) Derive overall acceleration or Δv cost and repeatability for limit cycling with 0.25 deg deadband at various Sun-relative attitudes, especially those foreseen to support SRC release. Most of these limit cycle tests entail attitudes away from Earth point and are more conveniently performed between DSN passes with small forces data stored and played back during later transmission.

3) Assess performance of smallest likely entry TCM (0.25 m/s) at fixed attitude via three Entry Maneuver Demonstrations (EMDs). Although actual TCMs would be pointed as indicated in Table 1, the high-gain antenna (HGA) along +z must necessarily be directed towards Earth to allow for real-time observation of radiometric data from the ground.

TEST SCHEDULE

The schedule carried out to meet these objectives is shown in Table 2. For the purposes of the 1-AU tests, slews were not studied as previous efforts to characterize slews have failed. Therefore, it is expected that all efforts will be made to design the return such that deadband walks could be used in the vast majority of cases. In addition to the activities shown in Table 2, TCM-9 served as an additional target of opportunity for performing a 1 m/s EMD, as the nominal burn direction required to clean up execution errors arising from DSM-3 placed the HGA of the spacecraft relatively close to Earthpoint.

Start (UTC)	End (UTC)	DSN	1-AU Test Activities
JUN 23 19:05	JUN 24 01:30	26 (Goldstone)	Entry Maneuver Demonstration (**EMD-1** ~22:00 ET); all EMDs 0.25 m/s at HGA Earth point.
JUN 24 10:00	JUN 24 17:20	63 (Madrid)	5° **DBW** test sets (7 roll, 8 pitch); walks usually start at least one hour into pass from MGA Earth point.
		off.	40° **DBW** test sets (4 pitch) from MGA Earth point.
JUN 25 01:25	JUN 25 05:30	43 (Canberra)	Return to HGA Earth point for playback.
JUN 25 19:45	JUN 26 01:30	15 (Goldsone)	**EMD-2** (~22:00 ET)
		off.	**Limit Cycle Test #1** -Simulated SRC Release Attitude.
JUN 27 01:25	JUN 27 05:25	43 (Canberra)	Return to HGA Earth point for playback.
JUN 27 12:05	JUN 28 01:30	63-26 (M/G)	5° **DBW** set (3 roll, 2 pitch) and 15° DBW set (1 roll, 1 pitch)
		off.	**Limit Cycle Test #2** -Same Attitude as #1.
JUN 28 12:00	JUN 28 17:20	63-26 (M/G)	15° **DBW** set (1 roll, 2 pitch)
		off.	**Limit Cycle Test #3** -Same Attitude as #2.
JUN 29 15:55	JUN 30 05:30	15-43 (G/C)	Backup for EMD and/or additional playback.
JUN 30 08:10	JUN 30 17:35	65 (Madrid)	**EMD-3** (~14:00 ET)
		off.	**Limit Cycle Test #4** -Simulated TCM-20 Attitude.
JUL 01 16:00	JUL 02 05:30	14-43 (G/C)	15° **DBW** set (5 roll, 5 pitch)
JUL 02 17:40	JUL 03 01:35	14 (Goldstone)	Final 15° **DBW** set (3 roll, 2 pitch, last 4 in opposite direction from previous tests)
		off.	**Limit Cycle Test #5** -Simulated TCM-20 Attitude.
JUL 03 17:30	JUL 04 00:15	26 (Goldstone)	Return to HGA Earth point for playback.

Table 2. 2003 1-AU Activities Correlated with DSN Passes According to Earth Receive Time (ERT)

TEST RESULTS AND ANALYSIS

Results of the three categories of tests (EMDs, limit cycle tests and deadband walks) were collected and analyzed. Of the three, deadband walks were tested the most extensively and as such, will be addressed first.

Deadband Walks

During the two week period, 88 separate deadband walks were executed in pairs (out from and back to MGA Earth point), totaling 44 test sets or pairs for various turn angles, as described in Table 2. Each walk starts out with the controller being commanded to propagate the reference quaternion (to which the attitude is controlled) by 1.5 deg/min to the target attitude. This causes the spacecraft to fire the RCS thrusters several times in order to induce the spacecraft to drift in the appropriate direction, at or near this maximum rate. After the reference quaternion is propagated through the appropriate turn angle, the ACS now controls the spacecraft to the new attitude, firing the opposite pair of thrusters several times when the spacecraft rotational velocity inevitably causes it to bump against the new deadbands. A typical signature for this event is visible in Figure 3, which displays a plot of accumulated small force Δv over the course a complete deadband walk to and from a target attitude.

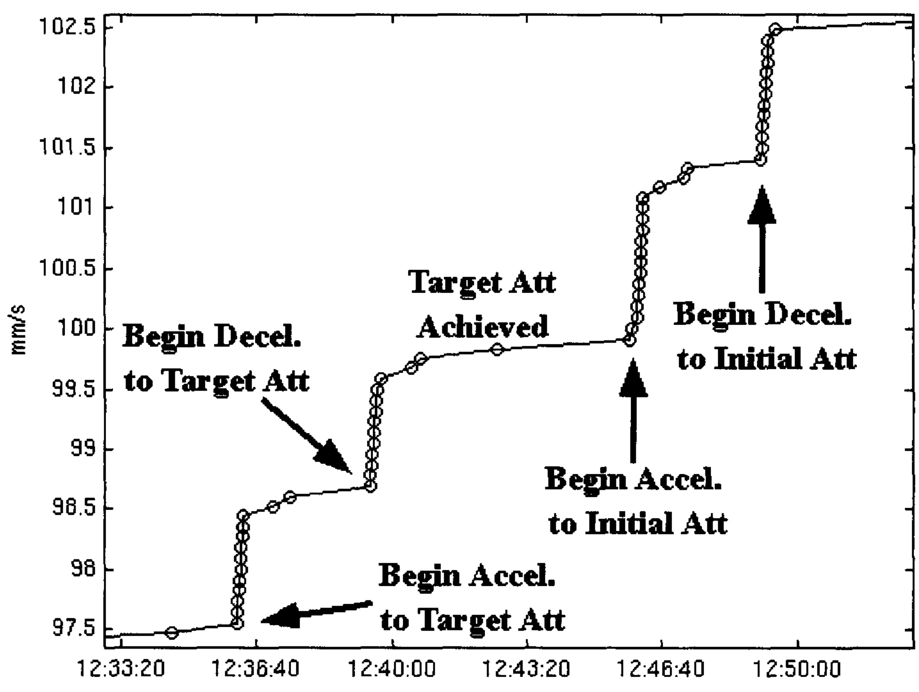

Figure 3. Example showing accumulated Δv per thruster pulse for an example Deadband Walk performed on June 24th (DOY 175) during the 2003 1-AU Tests.

Observed velocity changes are derived from the individual thruster firing events that are reported in telemetry as small forces data. These are corrected using OD-computed scale factors from a converged OD solution, and then summarized to assess the expected Δv for the event. Table 3 lists the calculated means and variances of the Δv for various categories of deadband walks. Note that each set consists of a complete activity, i.e. one roll out and one roll back, or one pitch out and one pitch back. Based on observations of all deadband walk types tested, 5 deg walks appear better behaved than 15 and 40 deg walks. Note that the mean of the 40 deg pitches seems to be less than that of the 15 deg pitches. However, the statistical confidence in this result is somewhat less than for the 5 and 15 deg walks, since there were fewer 40 deg walks. Table 3 also indicates how quantified errors from different sources (i.e., pitches and rolls) could be combined to derive execution errors for TCMs, according to the latest maneuver design and implementation strategies envisioned for return operations in 2005-2006, including final activities described in Table 1.

Size	Type (Walks per Set)	Sets (Out and back)	Mean (mm/sec)	Std. Dec. (mm/sec)
5	Pitch (2)	10	3.731	0.335
	Roll (2)	10	5.314	0.195
	For TCM (Rolls + Pitches)	---	*9.045*	*0.387*
15	Pitch (2)	10	4.177	0.599
	Roll (2)	10	6.672	0.310
	For TCM (Rolls + Pitches)	---	10.849	0.674
40	Pitch (2)	4	6.001	1.004
	For TCM (15 ° Rolls + 40 ° Pitches)	---	12.673	1.051

Table 3. Δv Statistics for Deadband Walks, based on OD-updated small force events.

Limit-Cycle Deadbanding

During the 1-AU testing, the spacecraft was observed for two weeks in 0.25 deg deadbands. The attitude during much of this time was spent at Earth point. In an attempt to further characterize the behavior of the small forces, the spacecraft also spent several hours in two possible simulated SRC release attitudes with respect to the Sun direction. Table 4 contains the acceleration seen along the spacecraft +z direction in mm/sec per day as a function of various Sun-relative attitude states.

Limit Cycle Attitude	Mean (mm/sec/day)	Std. Dev. (mm/sec/day)
Earth Point (Near Sun)	36.176	2.7014
SRC Release (~26 ° off Sun)	32.9495	3.6343
SRC Release + 18 ° Roll	45.4038	3.8248

Table 4. Limit-Cycle Deadbanding Effective Acceleration Along Spacecraft +z-axis.

Entry Maneuver Demonstrations (EMDs)

During an Entry Maneuver (TCM-20, see table 1), the spacecraft is expected to burn in an attitude that is the same as the SRC-release attitude. The attitude will be such that the maneuver will correct only the flight path entry angle.

It is important to characterize the spacecraft behavior before, during and after the execution of an entry maneuver, especially with regard to velocity uncertainties present in each phase. Once these errors are understood, it will be possible to assess the feasibility of the current Earth return strategy, as outlined in Table 1. This assessment will be aided by covariance analyses [1] of studies that take into account various combinations of error sources described later in this section.

EMD Sequence and Deconstruction

The EMD sequence employed for the 1-AU tests is based on the current sequence for a TCM, which off-pulses the thrusters during the main burn as a means of maintaining the desired thrust direction. The EMD sequence is composed of ten steps. These do not include any spacecraft attitude changes (slews or walks) required to attain a target attitude prior to the burn and return to the initial attitude after completion of the burn (both of these are normally required for a conventional turn-burn-turn TCM design). Figure 4 shows the location of the Earth with respect to the pointing of the spacecraft +z axis during all steps of the EMD performed at TCM-9. The ±0.25 deg deadband box is superimposed on the diagram for steps in which a new reference quaternion is set.

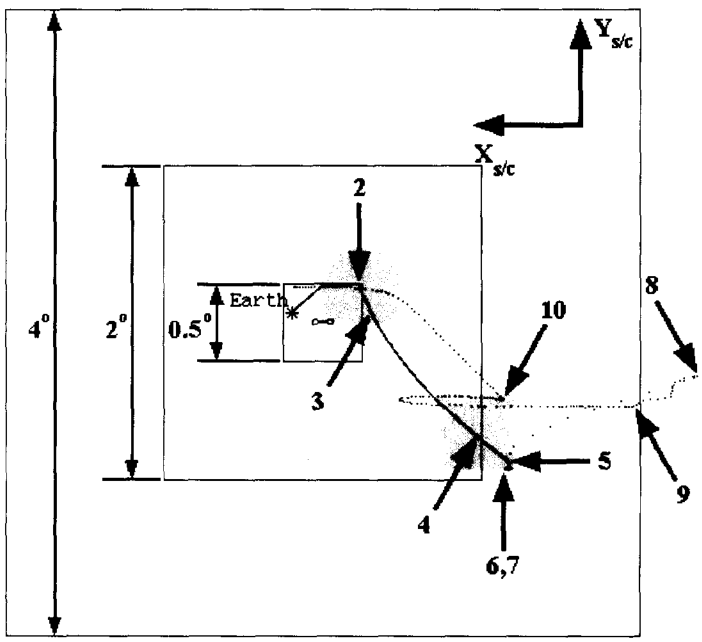

Figure 4. Steps in Current EMD Sequence as Executed for TCM-9. View shown is location of Earth as seen with respect to the direction off the spacecraft +z axis during all steps (z-axis into the page).

The steps (both commanded and observed) for an EMD are as follows:

1) *Clamp to 0.25 deg Deadband* – The spacecraft attitude controlled is commanded to enforce 0.25° deadbands. This was not necessary during the 1-AU testing, since the spacecraft is already in 0.25° deadbands;

2) *Rate Damping* – The rate by which the spacecraft is drifting is reduced before the accelerometers are calibrated; during this period one to three small force packets are generated where the resulting Δv and uncertainty can be expressed roughly as 0.15 +/- 0.08 mm/sec.

3) *Accelerometer/IMU Calibration* - During this calibration, which is 5 minute long, ACS is idling so that no small forces are produced; this allows the spacecraft to drift, resulting in an off-pointing of the spacecraft from the nominal attitude (to be discussed further in step 4). One or two small force events that would normally have maintained attitude within tight deadbands do not occur. The effect of such forces is roughly comparable to the effect of the additional small forces noted during the rate damping in step 2. During this drift, due to the strong solar torque present at 1-AU, the eventual pointing discrepancy is biased in the spacecraft +x direction. The magnitude of this drift is approximately 1 +/- 0.25 deg, depending on the effectiveness of the rate damping combined with the magnitude of the solar torque at that particular spacecraft attitude and distance from the Sun. Since all three EMDs and TCM-9 were performed in the Earth line-of-sight (LOS) direction, the SP+Z (Sun-Probe-Spacecraft Positive z) angles are comparable to each other, but not necessarily comparable to the SP+Z angle at SRC release attitude. For Earth return analysis, this contribution of this effect is inferred by comparing the solar torque present during limit cycling at 1-AU during Earth point and SRC release attitudes per Table 4.

4) *Setting of New Reference Quaternion* - Following the accelerometer/IMU calibration, ACS resumes attitude control, and uses the current attitude as the new reference quaternion. Future EMDs and the actual Earth entry maneuvers themselves will mitigate this pointing error by either re-targeting to the nominal burn attitude, or doing without the accelerometer calibration altogether.

5) *Rate Reduction before the Burn* - Like the rate reduction (step 2) before the start of the accelerometer cal, an additional rate reduction step is taken due to the accelerated drift as a result of the solar radiation pressure acting on the spacecraft. This also results in an expected one to three small force events.

6) *Initiation of Burn* - Since there is no correction of the post-IMU cal drift attitude pointing during the 1-AU EMDs, the attitude to which the burn vector is controlled has an a priori error of approximately 1 +/- 0.25 deg on average.

7) *Burn Execution* - During the burn, the ACS monitors the accumulated velocity based on calibrated accelerometer data. When the desired velocity is achieved, the burn terminates. Any calibration errors in the accelerometers (or other possible programmatic uncertainties) result in a burn execution error. Current EMD performance is presented in Table 5. Note the consistency and repeatability of the burn Δv for first three EMDs, all 0.25 m/s nominally.

8) *Burn Transient* - During a first 10 to 15 seconds of a nominal burn, in which the TCM thrusters fire at 100% duty cycle[1], an additional attitude diversion of up to 1-2 deg about the y-axis from the desired thrust direction occurs for two reasons: 1) The difference between the center of thrust (CF) and the center of mass (CM) of the spacecraft, and 2) the uncertainty in knowing the true CM. This behavior is best demonstrated in larger TCMs, such as DSM-3 (performed in two parts of about 35-36 m/s each on 17-18 June, just prior to the 1-AU test period). Figure 5 includes plots of both attitude and body rate errors for the first part of DSM-3, based on transient and steady state attitude telemetry. The current EMD sequence was originally designed with larger burns like DSM-3 in mind. The effect on all three spacecraft axes is shown, but the y-axis errors are of greatest significance. The attitude error plot shown in Figure 5 indicates that it takes 10-20 sec for the controller to start effectively correcting the burn vector; this results in a small side velocity error.

9) *Attitude Rectification after the Burn* - Due to the CF/CM difference (see step 8, above), there is an off-pointing of spacecraft attitude with respect to the burn vector of approximately 1 deg (see steady state y-axis attitude error telemetry in Figure 5). Following the termination of the burn, ACS attempts to correct what it perceives as a 1-deg attitude error. The small forces resulting from this correction need to be considered carefully in order to ascertain how much of it is systematic. In the case of the 0.25 m/s EMDs, the spacecraft was still going through the burn transients when the maneuver cut off, resulting in ACS having to correct a rate error before correcting the attitude error (see the rate error plot in Figure 5).

10) *Re-orientation* - Once the attitude is under control, ACS is commanded into the auto-reference Earth-point mode. This is when the attitude drift incurred during the IMU cal is corrected (see step 6). In the proposed nominal case, this correction will either occur before the burn, or not at all if the IMU cal is waived. The effect of the correction (either before or after the burn) on the spacecraft is the addition of a small roll/pitch walk on the spacecraft, and the accompanying small force Δv.

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[1] Verified by observing thruster "on-time" telemetry during start of TCMs and EMDs, which show that thrusters operate at nearly a 100% duty-cycle for the first 10 seconds of a burn,

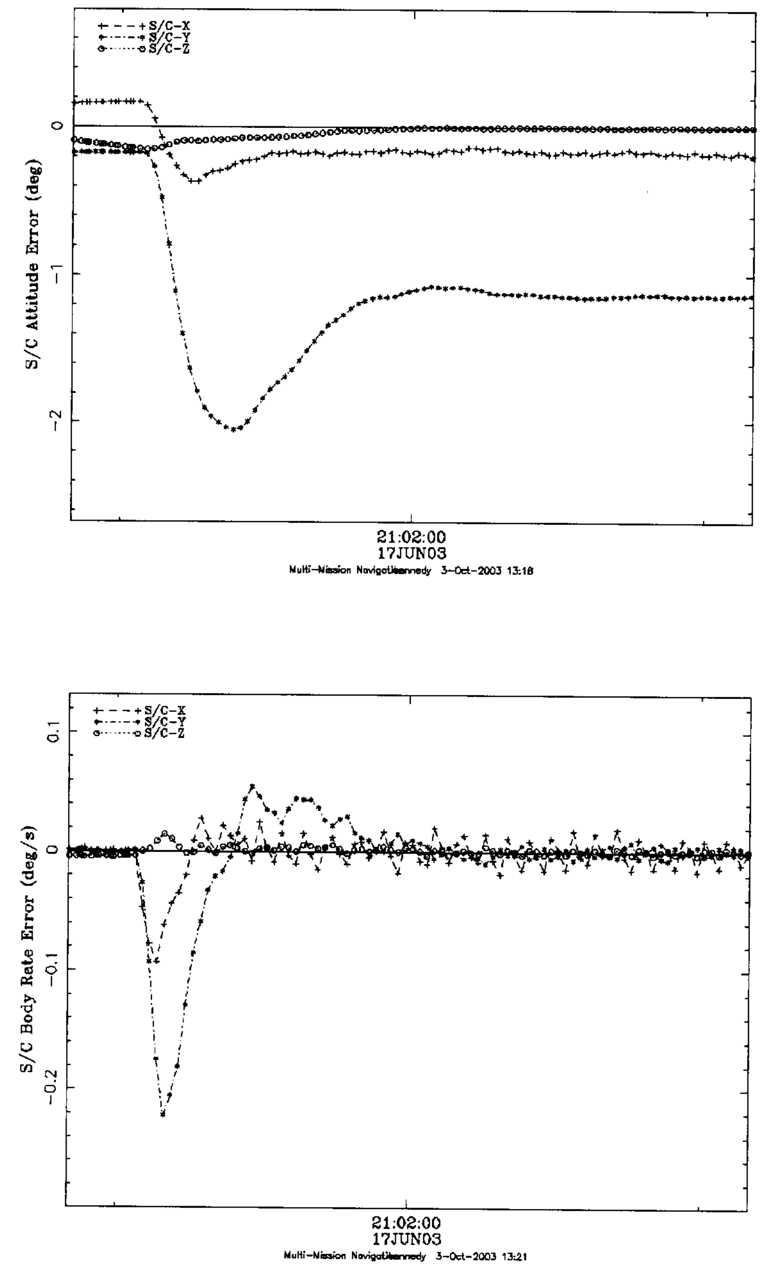

Figure 5. DSM-3 Attitude and Body Rate Errors. Transient error signatures are observable in the first 10 seconds of the burn. Steady-state errors follow. (The tick marks on the X-axes represent 1-minute intervals.)

Test	Case	Burn Δv (cm/sec)	Settling Δv (cm/sec)	Total Δv (cm/sec)
EMD-1	A: Design (nominal)	25	0	25
	B: Reconstruction	24.97	1.85	26.82
	B-A	-0.03	1.85	1.82
EMD-2	A: Design (nominal)	25	0	25
	B: Reconstruction	24.97	1.32	26.29
	B-A	-0.03	1.32	1.29
EMD-3	A: Design (nominal)	25	0	25
	B: Reconstruction	24.96	2.05	27.01
	B-A	-0.04	2.05	2.01
TCM-9	A: Design (nominal)	100	0	100
	B: Reconstruction	100.07	1.50	101.57
	B-A	0.07	1.50	1.57
	Mean -- >	-0.08%	1.68 cm/sec	
	Std Dev of Mean -->	+0.10%	0.33 cm/sec	
	Std Dev-->	+0.14% (0 mean)	1.60 cm/sec (for mean of ~1)	

Table 5. EMD Burn Performance

EMD PERFORMANCE CASES

Based on different assumptions about the EMD sequence design, associated ACS controller and how well observed uncertainties might be characterized, four different cases are considered:

- *Current* - None of the potential improvements to the EMD sequence are considered, but it is assumed that a systematic error of about 1.68 cm/sec can be compensated for when designing the maneuver; this is based on the mean of the settling errors derived from EMDs 1, 2 and 3 and TCM-9, as shown in Table 5. It is highly optimistic that such a systematic error could be assumed based on only four samples.
- *Current Worst* – Same as current case, except with an assumption of only 1 cm/sec systematic error (less than the minimum observed settling error of 1.32 cm/sec); this case is probably more realistic than the current case.
- *Improved* – An improved EMD sequence can also be considered, in which the attitude is commanded back to the original target attitude prior to initiation of the burn (see step 6 of "EMD Sequence and Deconstruction," above) using deadband walks, thereby minimizing settling error. Alternatively, elimination of the accelerometer cal from the sequence might have a similar effect (see step 3), albeit with some risk of increasing the burn execution error itself.
- *Improved Best* – Same as improved case, but with additional modifications to ACS controller to reduce error (e.g., reduction of duty cycle suggested in step 8).

EMD SOURCES OF ERROR

The execution errors listed above are further quantified to fit the following error types, as described in [3]: fixed magnitude, proportional magnitude, fixed direction and proportional direction error. Table 6 and the following subsections contain this additional breakdown of the different cases that are being studied, specifying error sources and their contribution to the various classes of error.

Fixed Magnitude Error

Fixed magnitude error encompasses several sources arising from small forces during pre-cal (see step 2 of "EMD Sequence and Deconstruction," above) and post-cal rate reduction (step 5) and attitude re-orientation (step 10). These affect all four cases described above. For current and current worst cases only, there are also small forces during post-burn rate and attitude correction (steps 8 and 9).

Proportional Magnitude Error

Proportional magnitude error arises from variation in the point at which the ACS cuts off the burn based on the calibrated accelerometer data (see step 7). This affects all scenarios.

Fixed Direction Error

Fixed direction error is the side velocity error computed from the initial slew (about the y axis) that occurs during the transient phase of the burn (step 8) for the current and current worst cases. This effect is significantly reduced for improved case, and even more so for the improved best case.

Proportional Direction Error

Proportional direction error encompasses the following effects:

- For all scenarios, the inertial direction to which the burn vector is controlled is not necessarily tied to the spacecraft reference attitude. During the inertial hold and before the burn starts, the spacecraft is pointing somewhere with the current deadbands nominally, but not necessarily within the center of the deadband box (see step 5, "EMD Sequence and Deconstruction," above).
- For current and current worst scenarios only, during the 5 min IMU cal drift, the spacecraft can drift through an angle of 1-2 deg. At the end of the drift, the new attitude is used as a basis for the new reference attitude, which correspondingly results in a large direction error for the burn (see steps 3, 4 and 6).

Case	Fixed Magnitude (m/s, 1σ)	Fixed Direction (m/s, 1σ)	Proportional Magnitude (%, 1σ)	Proportional Direction (%, 1σ)
Current	0.0033	0.0073	0.14%	1.31%
Current Worst	0.0160	0.0073	0.14%	1.31%
Improved	0.0028	0.0027	0.14%	0.14%
Improved Best	0.0028	0.00135	0.14%	0.14%

Table 6. Expected Execution Errors Based on EMD Deconstruction.

ANALYSIS AND FURTHER WORK

To assess the impact on Earth entry of observed limit cycle, deadband walks and EMD performance, Monte-Carlo studies were performed utilizing several simulations. Each test case scenario mentioned in Table 6 was addressed to ascertain the effectiveness of meeting the requirements for successful Earth entry. Detailed description of the set-up and execution of these analyses is beyond the scope of this paper, but all aspects of said analysis are fully discussed in reference [1].

The conclusion of the scenario analyses discussed in [1] did show that for the "current case" and "current worst case" scenarios, the percentage of successful cases (in which the FPA was within the 0.08° allowance) was well below 99%. However, the "improved case" and "improved best case" scenarios showed effectively similar success rates in excess of 99%. Based on this, it is apparent that modifying the EMD sequence to remove the burn direction error incurred after the accelerometer calibration is essential (please refer to the description of the "improved case", above). Removal of this direction error can be effectively accomplished by either reasserting the desired attitude, or forgoing the calibration entirely (please refer to steps 9 and 10 of "EMD Sequence and Deconstruction," above). A future trade study will need to be performed to ascertain over what Δv ranges which of these directions might be more appropriate[2]. It is expected that examination of past accelerometer stability will need to be performed in order to effect such a study.

Since both the "improved case" and "improved best case" scenarios showed such like success rates, it was decided that the side velocity errors incurred during the initial burn transients is acceptable. Therefore, efforts to minimize this by reducing the duty cycle of the TCM thrusters during burn start-up will not be necessary[3]. However, it is expected that any Entry Maneuver be of sufficient magnitude that the attitude burn controller has reached its steady state by the time the burn cutoff is reached (see Figure 5 for an example of initial transients seen in the attitude and rate errors during a burn). If the burn cutoff is reached while still in a transient control state, the ACS will be tasked to correct these errors using the small RCS thrusters, resulting in large amounts of unexpected Δv imparted to the spacecraft. The full impact of executing a smaller than 0.25 m/s Entry Maneuver has not been explored fully, although examination of the current set of test cases for each scenario seems to indicate that the likelihood of such an event is small. It is

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[2] There presumably exists a maneuver magnitude at which proportional errors incurred by burning with an uncalibrated (but not necessarily poorly calibrated) accelerometer begin to overwhelm any fixed errors incurred from retargeting following a cal drift.

[3] It is acknowledged that these efforts might have required a change to the flight software, and would therefore have been prohibitively expensive.

still possible that alternative means of imparting relatively small (~10-20 cm/s) Δv onto the spacecraft will need to be explored.

It was also noted in [1] that a subset of "improved" and "improved best" test cases could be identified as having required slews as part of the execution of one (or more) of TCMs 17, 18 and 19. If these specific test cases are ignored, then the success rates for the "improved" scenarios improve to 99.9% (well over 3-σ). It bears repeating that it is considered necessary for mission success that all transitions to burn attitudes leading up to Entry be performed with deadband walks. If the desired burn attitude takes the spacecraft +z-axis more than 45° off of the Sun, a slew is considered necessary since the time taken for deadband walks to and from these attitudes would leave the spacecraft in a power-negative situation for too long. Designing a Sunward bias into the maneuvers (see Table 1) allows for a large number of burn attitudes to fall within this range, but increasing this range is recommended to cover the greater statistical variability in burn attitudes. To that end, the possibility of using faster deadband walks will be explored. During the next year of deep space cruise, the spacecraft will deadband walk to telecommunication attitude on a weekly basis. These weekly walks will occur at a rate of three degrees per minute (as opposed to the nominal 1.5 degrees per minute). Analysis of these walks is expected to provide insight into the efficacy of performing fast walks at Earth Return. If these data can be used to extrapolate the Δv expected for a fast walk at 1 AU, then new Monte-Carlo simulations will be performed to fully assess their effectiveness.

Not all error sources were explored as candidates for possible mitigation. Of these, the Δv incurred as a result of correcting the immediate post-burn attitude error is considered a large part of the settling Δv (please refer to Table 5, above, and step 9 of "EMD Sequence and Deconstruction," above). It is possible that a majority of this settling could be avoided if the ACS can be sequenced or configured into adopting the post-burn attitude as the new reference attitude. If feasible, this method can be folded into any future EMD tests that might be performed.

Lastly, new ground procedures will need to be developed to incorporate the deadband walks into any maneuver implementation sequence. Presently, all maneuvers are implemented as slew-burn-slew. These new procedural changes are currently work in progress and are addressed further in reference [1]. The next available opportunity to apply this knowledge will be on February 3rd, during TCM-15.

CONCLUSIONS

Based on the analyses performed on the data derived from these 1-AU tests, it appears that the new Earth Return strategy will allow the Stardust spacecraft to achieve Earth Entry conditions 99% of the time. This is provided that certain steps within the current EMD sequence are mitigated, and that all TCMs performed on Earth Approach are transitioned to via deadband walks. Although there remains work and analysis to be done, including further spacecraft calibration activities in early 2005, there is much confidence that with further refinements Stardust can meet the FPA entry requirement with a 3-σ (99.7%) level of success.

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REFERENCES

[1] K. E. Williams, "Earth Return Maneuver Strategies for Genesis and Stardust," AIAA/AAS Astrodynamics Specialist Conference, Maui, HI, February 8-12, 2004.

[2] C. L. Potts and P. R. Menon, JPL Interoffice Memorandum 312.H-00-001, *A Priori Stochastic Non-Gravitational Acceleration Effects on Stardust Navigation earth Entry Covariance,* 9 March 2000.

[3] J. P. Slonksi, JPL Interoffice Memorandum 3131-83-249, *Explanation of Maneuver Execution Accuracy Specification*, 28 November 1983.